A Line-of-Sight Optimised MIMO Architecture for Outdoor Environments

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Abstract— **The authors present an investigation on the capacity of Line-of-Sight (LoS) optimised and conventional (narrow-spaced) Multiple-Input Multiple-Output (MIMO) communication systems in outdoor environments. Under a LoS scenario, the channel is normally rank deficient due to the linear dependence of the LoS rays' phases on the receive elements. To overcome this problem, specifically designed antenna arrays can be employed, where the antenna elements are positioned to preserve the orthogonality of the LoS signal at the receiver; hence maximising the channel rank. A previously derived maximum capacity criterion is employed in the design of the proposed LoS-optimised MIMO system. The performance of this system is then assessed by means of a ray-tracing simulation and compared with that of a conventional MIMO system. It is shown that the proposed system exhibits a significant capacity enhancement (45.3 %) in the deployment area. Moreover, the capacity was found to be higher than that predicted by the i.i.d. Rayleigh fading model due to non-fading nature of the LoS signals.**

I. Introduction

Given the scarcity, and thus the rising value of radio spectrum, Multiple-Input Multiple-Output (MIMO) technology is considered as a key technology for future high-bandwidth communication systems. It has been shown that MIMO technology can, in principle, offer a linear increase in capacity that is proportional to the minimum number of transmit and receive elements [1]. This capacity enhancement is attributed to the utilisation of multiple spatial subchannels between the transmit and receive elements. In practical systems however, the spectral efficiency is limited by the number of uncorrelated communication paths between the transmitter and receiver. In systems with highly correlated channel responses only a few subchannels effectively contribute to the total capacity of the system and therefore the performance of the system is lower than that predicted by an i.i.d. Rayleigh fading model [2], [3].

One example where a correlated MIMO channel can occur is in the case of the transmit and receive arrays being in Line-of-Sight (LoS). This is accounted to the fact that in most conventional MIMO systems the transmit and receive arrays are in the far field;[1] thus, the spatial signatures of the received signals are almost identical. Under such conditions the capacity is effectively equivalent to that of a Multiple-Input Single-Output (MISO) system [2]–[4].

Contrary to these observations, a number of studies have shown that by using specifically designed antenna arrays the orthogonality of the received signals can be preserved [5]–[8] and a number of methods for the design of LoS-optimised antenna arrays were previously reported [9]–[12]. In this paper, the authors investigate the performance of LoS-optimised and conventional MIMO systems in an outdoor environment using a ray-tracing propagation model. The configuration examined in this paper involves a number of high-mounted (lamp-post level) Access Points (APs) providing wireless access to Mobile Terminals (MTs) at street-level. The proposed architecture consists of antenna arrays that satisfy the maximum capacity criterion derived in [9], [10] whereas the conventional systems consists of a set of narrow-spaced antenna elements. The results provide a valuable insight into the levels of capacity that can be expected from both systems in practical environments.

The paper is organised as follows: Section II outlines the system model employed in this investigation and presents some information about the ray-tracing model and the MIMO channel capacity. In Section III the deployment strategy for the simulation is described whereas the results of this study are presented in Section IV. Section V compares the ray-tracing results with a geometric model and Section VI outlines the conclusions from this study.

II. Channel Model and Capacity

The system model assumed throughout this paper involves a communications system with 2 transmit and 2 receive elements (from now on referred to as a 2×2 MIMO system) impaired by Additive White Gaussian Noise (AWGN). The complex baseband input-output relationship for this system can be represented mathematically by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{1}$$

where $\mathbf{y} \in \mathcal{C}^2$, $\mathbf{H} \in \mathcal{C}^{2\times 2}$, $\mathbf{x} \in \mathcal{C}^2$ and $\mathbf{n} \sim \mathcal{CN}(0, \sigma_n^2)$ correspond to the received signal vector, the channel response matrix, the transmitted signal vector and the AWGN noise vector respectively.

[1] i.e. $D >> \frac{2s^2}{\lambda}$, where D is the distance between the arrays, s is the largest dimension of the array and λ is the wavelength.

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A. Ray-Tracing Channel Model

The channel response is determined by a previously developed MIMO-capable ray-tracing model. The use of this model provides accurate estimates for the Channel Impulse Response (CIR) at both ends of the link, without the need for specific assumptions. The tool used in this paper traces electromagnetic waves in 3-D space and takes into account individual buildings, trees, corner and roof-top edges, terrain blocking and scattering. The ray model has been previously validated using measurement data collected in mixed urban and rural environments at 1.8 GHz and 5.2 GHz [13], [14] and has been used in numerous studies in the past including [15].

B. MIMO Capacity

In all investigations the receiver is assumed to have perfect channel knowledge, whereas no such prior knowledge is available at the transmitter. Moreover, the transmit power is equal to $P_t/2$ at both transmit elements. The capacity of such a system is given by

$$C = \log_2 \left(\det \left(\mathbf{I}_2 + \frac{\rho}{2} \mathbf{H}\mathbf{H}^H \right) \right) \tag{2}$$

where $\mathbf{I}_2$ is the 2×2 identity matrix, ρ corresponds to the average received Signal-to-Noise Ratio (SNR) at the input of the receiver and $[\,.\,]^H$ denotes the (Hermitian) conjugate transpose [1].

III. Experimental Setup

This section describes the experimental setup for the ray-tracing simulation study. In detail, the deployment environment is described along with two deployment scenarios that correspond to the conventional and the proposed MIMO architectures. For this study an operating frequency of 5.2 GHz was chosen.

A. Deployment Area and LoS-optimised Configuration

The deployment area for this ray-tracing study is based on a vector database of a 2 Km^2 area in central Bristol (U.K.). In this area, a city council operated wireless network (802.11b) is currently in use. The following investigation examines the potential of a future MIMO upgrade of this network for the 802.11n standard. To minimise the complexity of the system a 2×2 MIMO configuration is assumed.

A previously derived maximum capacity equation is employed in the design of the LoS-optimised MIMO architecture. For a 2×2 MIMO system this is expressed by the following equation:

$$s_1 s_2 \approx \left(\frac{1}{2} + p \right) \frac{\lambda D}{\sin \omega \sin \theta} \;\forall\; p \in \mathbb{Z}^+ \tag{3}$$

where s_1, s_2 correspond to the spacing in the two arrays, D is the Transmitter (T) to Receiver (R) distance, $\mathbb{Z}^+$ corresponds to the set of positive integers and the angles ω and θ correspond to the geometry of Fig. 1.

Due to the large value of D in an outdoor deployment scenario and given the need to reduce the array size at the mobile side

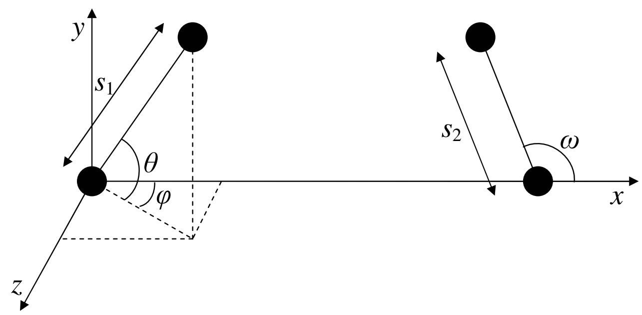

Fig. 1. Positioning of the elements in a 2×2 MIMO system

(s_2), much greater element spacings are needed at the AP (s_1). Thus, a distributed MIMO system is proposed where the inter-element spacing on the AP is of the order of the distance D. Then assuming that the AP elements are deployed at a lamp-post level (height = 10 m) and that the requirement for the MT spacing is in the order of a few centimetres the optimal spacing at the AP can be found to be ≈10 m in the middle of the road width (≈12 m).

During this investigation it was also found that in order to satisfy the maximum capacity criterion as closely as possible over a large area, multiple antenna elements positioned along the length of the road were required. However, at each point on the road only the two AP elements closest to the MT would be used for communication. The exact positioning of the antenna elements is described in more detail in the following paragraph.

B. Deployment scenarios

For the purpose of comparison between conventional and LoS-optimised MIMO architectures, two systems are considered: Scenario 1) a system with 2-element access points and Scenario 2) a distributed MIMO system with single-element access points. In the first scenario, ten access-point sites were deployed, each site comprising of two elements with a separation distance of 20 cm. The sites were located along both sides of the road in intervals of 20 m (Fig. 2). For the second scenario, twenty access points (each comprising of a single element) were distributed along the same road in intervals of 10 m (Fig. 3). On the mobile terminal side two elements spaced by 4 cm are used for both scenarios. Note that at each point along the route, the two nearest elements to the mobile unit are used for communication, so at any time the system is a 2×2 MIMO configuration for both scenarios.

The capacity of the system is calculated for a number of MT locations (route-points) along a route. In detail, the mobile terminal starts from a non-LoS position (r.p. 1-79), goes into a LoS location and moves along the deployment area (r.p. 100-300). Finally, the terminal moves out of the deployment area and to a non-LoS position (r.p. 450-565). For all points along the route, the impulse response was recorded for each of the 20×2 MIMO subchannels. The corresponding channel response matrix

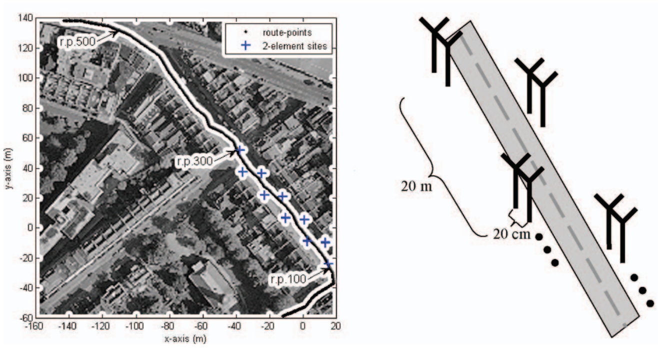

Fig. 2. Deployment Scenario 1

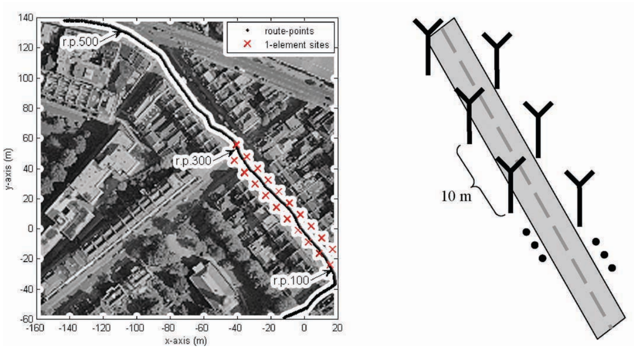

Fig. 3. Deployment Scenario 2

was acquired by taking into account only the four subchannels between the two MT elements and the nearest two AP elements.

IV. RESULTS

This section presents the results of the ray-tracing study corresponding to two extreme power control strategies. In the former, it is assumed that the transmit power is dynamically adjusted so that the SNR at the receiver is always constant (and equal to 20 dB); thus, simulating a system with perfect power control. The latter assumes a system with a fixed transmit power which does not depend on the received SNR; thus, corresponding to a system with no power control. The authors believe that it is essential to present the results for both power control scenarios so that a fair comparison can be made between the benefits from a high received SNR and a high multiplexing gain.

A. Results (Fixed SNR)

Here the MIMO capacity of the proposed and standard architectures are analysed independently of the average SNR. This is achieved by normalising the channel response matrix so that the following constraint is satisfied for each route point

$$E\{\|\mathbf{H}\|_F^2\} = 4 \tag{4}$$

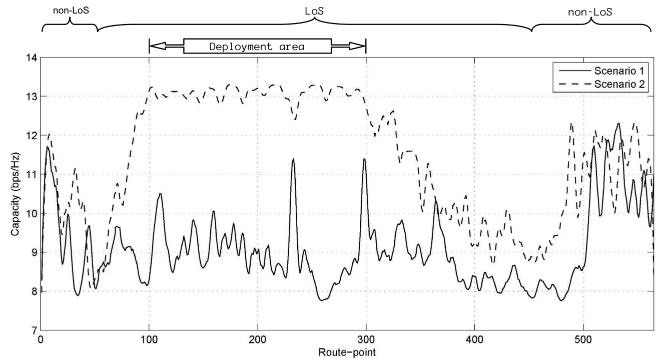

Fig. 4. Capacity as a function of the position of the mobile terminal in the route (ρ = 20 dB)

TABLE I

MEAN CAPACITIES FOR SCENARIOS 1 AND 2 ALONG DIFFERENT PARTS OF THE ROUTE (R.P.=ROUTE-POINT)

	non-LoS (r.p. 1-49, 450-565)	**Deployment Area** (r.p. 100-300)	**Total** (r.p. 1-565)
Scenario 1	9.59 bps/Hz	9.02 bps/Hz	9.10 bps/Hz
Scenario 2	10.56 bps/Hz	13.08 bps/Hz	11.45 bps/Hz
Impr/ment	10.1%	45.3%	25.7%

where $\| \,.\, \|_F$ corresponds to the Frobenius norm. The results are plotted in Fig. 4 for both deployment scenarios. .

Clearly, the LoS-optimised architecture shows a significantly superior performance in the deployment area than the conventional (narrow-spacing) deployment architecture scenario which demonstrates the problems faced by conventional MIMO systems in LoS environments. On the other hand, the performance of both architectures was found to be similar in non-LoS environments.

Table I outlines the numerical results of this study. Please note that the maximum MIMO capacity for an SNR of 20 dB is equal to 13.3 bps/Hz whereas the capacity predicted from an i.i.d. Rayleigh model for the same SNR is 11.4 bps/Hz. Thus, it is interesting to see that the LoS-optimised system achieved a higher capacity than that predicted from an i.i.d. Rayleigh model.

B. Results (Fixed Tx Power)

Maintaining a high SNR level at large distances from the AP requires a high transmit power which can cause high levels of interference to other users. Hence, the optimal transmit power control described in the previous Section is not always viable. Here the performance of a system with a constant transmit power (i.e. no power control) is investigated for both deployment scenarios. The results are plotted in Fig. 5. Again, the distributed configuration has exhibited a superior performance in the deployment area than the small-spacing scenario. However, the effect of low SNR further away from the deployment area is also demonstrated.

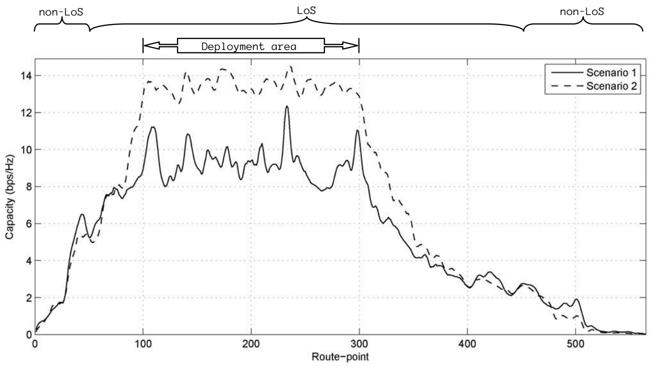

Fig. 5. Capacity as a function of the position of the mobile terminal in the route (constant transmit power)

TABLE II
MEAN CAPACITIES FOR SCENARIOS 1 AND 2 ALONG DIFFERENT PARTS OF THE ROUTE (R.P.=ROUTE-POINT)

	non-LoS (r.p. 1-49, 450-565)	**Deployment Area** (r.p. 100-300)	**Total** (r.p. 1-565)
Scenario 1	1.61 bps/Hz	9.31 bps/Hz	5.54 bps/Hz
Scenario 2	1.37 bps/Hz	13.44 bps/Hz	7.22 bps/Hz
Impr/ment	-14.9%	44.4%	30.3%

In detail, it is shown that both architectures suffer from a reduced capacity when the MT is either at a large distance or in a non-LoS location. This observation strengthens the argument for the need of either a comprehensive power control strategy or a LoS signal (and a LoS-optimised architecture) to enable high capacities in outdoor MIMO environments.

Table II outlines the numerical results of this study[2].

V. RAY-TRACING VS GEOMETRIC MODELLING

The results of Section IV in the deployment area showed an average capacity of 13.1 bps/Hz which is higher than the i.i.d. Rayleigh capacity (11.4 bps/Hz) and approaches the maximum limit of 13.3 bps/Hz. This indicates that the received signal was dominated by the LoS path for which the system was optimised. In this Section the suitability of a free-space geometric channel model is examined for scenarios where the LoS is much stronger than the power of the multipath rays.

In free-space, the complex response between a transmit element m and a receive element n (assuming isotropic elements) is equal to $e^{-jkd_{n,m}}/d_{n,m}$, where $k = \frac{2\pi}{\lambda}$ is the wavenumber corresponding to the wavelength λ and $d_{n,m}$ is the distance between the two elements. Assuming that the relative differences in path-loss are negligible, the normalised free-space channel

[2]Please note that the transmit power was chosen so as to provide an average SNR of 20 dB throughout the deployment area.

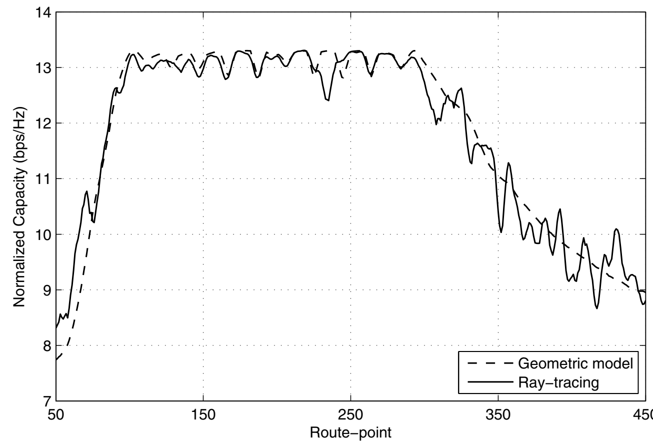

Fig. 6. Capacity as a function of the position of the mobile terminal in the route (constant Tx power)

response matrix of an 2×2 MIMO system can be written as

$$\mathbf{H} = \begin{bmatrix} e^{-jkd_{1,1}} & e^{-jkd_{1,2}} \\ e^{-jkd_{2,1}} & e^{-jkd_{2,2}} \end{bmatrix} \tag{5}$$

Clearly, the above matrix is deterministic and depends only on the distances between the transmit and receive elements [16]. To evaluate this matrix for the scenario of interest the Euclidian distance $d_{n,m}$ is extracted for all pairs of elements from the ray-tracing software and then the free-space LoS response between all elements is evaluated as $e^{-jkd_{n,m}}$. By using the same selection process as before the 2×2 channel matrix is formulated for each point. The resulting capacity is shown in Fig. V.

In this figure, the free-space capacity shows a very close agreement with the ray-tracing result which again can be accounted to the dominance of the LoS component in the total received power. In detail, it was found that the mean K-factor (i.e. the ratio of powers of the LoS and the scattered components) in the LoS locations was 11.21 dB with a maximum K-factor of 19.67 dB. The above investigation leads to the conclusion that in a scenario where a strong LoS exists (or equally the K-factor is high (above 10 dB)) the free-space geometric model can be accurately used to predict the MIMO capacity.

VI. CONCLUSION

This paper presented a method to achieve orthogonality between spatially multiplexed MIMO signals in LoS channels by employing specifically designed (LoS-optimised) antenna arrays. The performance of the proposed and a conventional architecture conditions was assessed by means of a MIMO-capable ray-tracing model assuming two extreme power control strategies. A very significant performance improvement ($\approx$ 45 %) was observed in both power control strategies over conventional MIMO systems in LoS whereas in non-LoS locations both deployment strategies exhibited similar capacities. The simulated capacities were also compared with a free-space geometric model where a close agreement was found throughout the deployment area due to the dominance of the LoS ray.

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